Sterile dark matter and reionization

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Sterile neutrinos with masses in the keV range can be the dark matter, and their emission from a supernova can explain the observed velocities of pulsars. The sterile neutrino decays could produce the x-ray radiation in the early universe, which could have an important effect on the formation of the first stars. X-rays could ionize gas and could catalyze the production of molecular hydrogen during the "dark ages". The increased fraction of molecular hydrogen could facilitate the cooling and collapse of the primordial gas clouds in which the first stars were formed.

There are several reasons to expect that cosmological dark matter is made up of right-handed, or sterile neutrinos. First, most model of the neutrino masses postulate the existence of the right-handed fields. Although it is not impossible to explain the neutrino masses otherwise, the seesaw mechanism [1] offers probably the most natural way of doing it. However, the seesaw mechanism can work equally well for the sterile neutrino masses well above [1] or well below [2,3,4] the electroweak scale. Each of these two possibilities offers a viable scenario for leptogenesis, in which the lepton asymmetry is generated by either the sterile neutrino decays [5], or by neutrino oscillations [6]. The current experimental constraints allow both possibilities [7].

Second, there are some additional astrophysical hints in favor of the keV sterile neutrinos. The observed velocities of pulsars [8] can be explained by the emission of sterile neutrinos from a supernova [9]. The magnetic field in a hot protoneutron star can grow via the dynamo action driven by the neutrino cooling at least until the saturation of the linear regime is achieved, which is for $B \sim 10^{16}$ G [10]. Since the growth is concentrated in the thin-shell convective zone, the exponentially growing modes on different sides of the star can develop in an uncorrelated manner [11], and the global structure of the field in the core need not be spherically or axially symmetric during the first seconds of the supernova. Hence, the field in the core can have a strong off-centered dipole component. The electrons in the hot protoneutron star are polarized by the magnetic field. Because of this, both the active and the sterile neutrinos are produced anisotropically, but for the active neutrinos the anisotropy is washed out by scattering [12]. In contrast, the sterile neutrinos escape without scattering, so their emission asymmetry equals the production asymmetry, and the recoil can give the neutron star a kick consistent with the observations [9]. The range of parameters consistent with this explanation of the pulsar kick is shown in Fig. 1. Numerical calculations of supernova explosion taking into account this mechanism for the pulsar kick show that the motion of the neutron star causes convection, which can deposit additional energy beyond the shock, thus helping the supernova explode [13].

In the early universe sterile neutrinos can be produced from neutrino oscillations [14,15,16] or from the inflaton decay [17] at some sub-GeV temperatures. They can also be produced in some other process, for example, in the singlet Majoron decays at some temperature above the electroweak scale [18]. Different production mechanisms generate neutrinos with different momentum distributions. To be dark matter, the relic population of sterile neutrinos must be sufficiently cold. For neutrino oscillations in the absence of lepton asymmetry, the Lyman-α bound is $m_s > 10$ keV [19]. If the lepton asymmetry of the universe is 0.01 or greater, resonant neutrino oscillations can generate the dark matter in

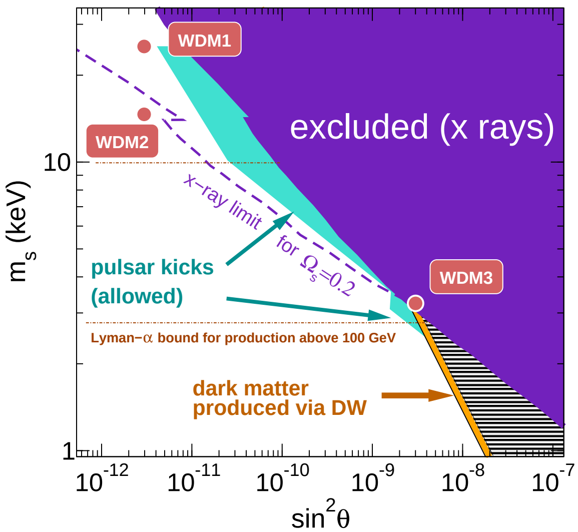

Figure 1. The limits on sterile neutrino mass m and mixing angle θ. Also shown are the three sets of parameters, WDM1-3, corresponding to the curves in Fig. 2. The dashed line shows the x-ray limit if the sterile neutrinos account for the entire dark matter. If the neutrino oscillations are the only production mechanism, the corresponding limits are weaker (the solid purple region) [18]. The Lyman-α lower bound on the dark-matter particle mass depends on the production mechanism. This bound is 10 keV [19] for the production via oscillations [14], but it is relaxed considerably if the population of relic neutrinos originates above the electroweak scale [18].

the form of sterile neutrinos even for very small mixing angles [16]. If the sterile neutrinos are produced above the electroweak scale, their momenta are redshifted, and the Lyman-α bound is relaxed from 10 keV to about 2.7 keV lower [18], as shown in Fig. 1.

Sterile neutrinos are stable on cosmological time scales, but they do decay into the lighter neutrinos and the x-ray photons. This two-body decay can be used to discover the sterile dark matter. The current x-ray limits [20] are shown in Fig. 1 in two ways: (i) assuming that the sterile neutrinos account for the entire dark matter (dashed line, $\Omega_s \approx 0.2$), and (ii) assuming that the sterile neutrinos are only produced via neutrino oscillations[14,15], in which case they may not be the dominant dark-matter component. The latter scenario provides a model-independent limit in any cosmology, except for the low-reheat scenarios [21]. Regardless of how the sterile neutrinos are produced, their decay width is related to the mixing angle, and to the fraction of matter they make up.

The same x-rays from sterile neutrinos can play an important role during the dark ages in the early universe. Although these x-rays alone are not sufficient to reionize the universe [22], they can catalyze the production of molecular hydrogen and speed up the star formation [23,24], which, in turn, causes the reionization.

Molecular hydrogen is a very important cooling agent necessary for the collapse of primordial gas clouds that give birth to the first stars. The fraction of molecular hydrogen must exceed a certain minimal value for the star formation to begin [25]. The reaction H+H→$H_2 + \gamma$ is very slow in comparison with the reaction

$$\mathrm{H}^+ + \mathrm{H} \rightarrow \mathrm{H}_2^+ + \gamma, \quad (1)$$

$$\mathrm{H}_2^+ + \mathrm{H} \rightarrow \mathrm{H}_2 + \mathrm{H}^+, \quad (2)$$

which is possible if the hydrogen is ionized. Therefore, the ionization fraction x_e determines the rate of molecular hydrogen production. If dark matter is made up of sterile neutrinos, their decays give out a sufficient flux of photons to increase the ionization fraction by as much as two orders of magnitude [23,24,26]. This has a dramatic effect on the production of molecular hydrogen and the subsequent star formation.

The x-ray photons from the dark matter decays affect the collapsing gas halos in two ways. First, they catalyze the formation of molecular hydrogen, which facilitates cooling. Second, they heat up the gas clouds, which might counteract cooling [24,26]. The interplay of these two effects was studied in Ref. [24] for three points in the allowed parameter space, WDM1-3, as shown in Fig. 1. The results for the molecular hydrogen fraction are shown in Fig. 2. In all three cases the the main effect of sterile neutrinos was to fa-

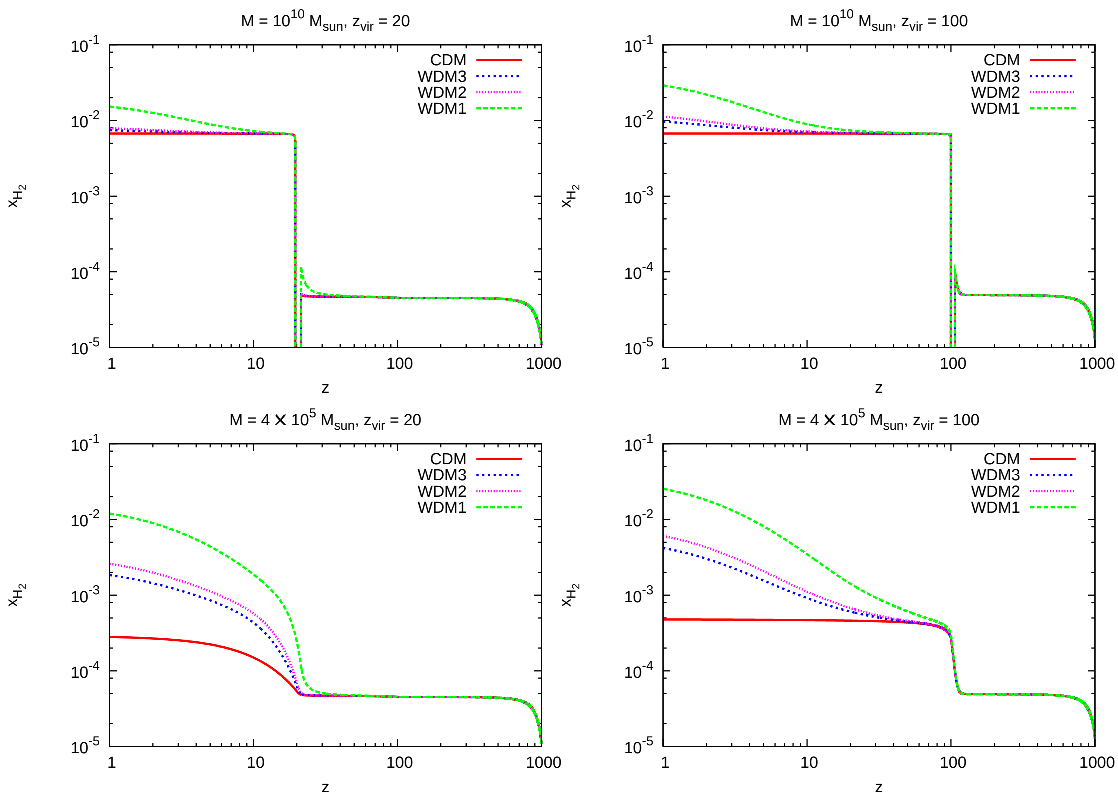

Figure 2. Evolution of the molecular hydrogen fraction with redshift [24] for three different models: $m_s = 25\,\mathrm{keV}$ and $\sin^2\theta = 3\times10^{-12}$ (WDM1), $m_s = 15\,\mathrm{keV}$ and $\sin^2\theta = 3\times10^{-12}$ (WDM2), $m_s = 3.3\,\mathrm{keV}$ and $\sin^2\theta = 3\times10^{-9}$ (WDM3). M is the cloud mass and z_{vir} is the redshift of virialization.

cilitate the collapse of the clouds and to speed up the star formation.

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